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Initial Analysis of Floating Fiber Embankment Construction: Working Principle, Material Characteristics, and Potential Applications in Coastal Areas

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ABSTRACT

Sea level rise due to climate change and land subsidence in coastal areas have increased the frequency of tidal flooding, especially in Indonesia. Conventional embankments that are generally used to hold back seawater have limitations in adapting to fluctuations in water levels. This study evaluates a floating fiber embankment as an innovative solution for tidal flood mitigation. The embankment is designed to automatically adapt to changes in sea level using elastic and corrosion-resistant fiber materials. Numerical simulations based on the finite element method (FEM) were performed using ANSYS software to analyze the stress, strain, and deformation of the floating fiber embankment under hydrostatic pressure. The simulation results showed a maximum stress of 8231 x 10^6 Pa with a maximum deformation of 0.43 meters. Laboratory experiments using a 1:20 scale prototype validated the simulation results, with a maximum stress of 8210 x 10^6 Pa and a maximum deformation of 0.41 meters. The results showed that the floating fiber embankment has good adaptive capabilities in resisting hydrostatic pressure and functions automatically without requiring manual intervention. This technology has the potential to be an effective and sustainable solution for tidal flood mitigation in coastal areas, especially in areas that often experience land subsidence and sea level rise due to climate change.

Keywords: floating fiber embankment; tidal flood; hydrostatic pressure; coastal area; mitigation.

INTRODUCTION

Global climate change and the impact of human activities on coastal environments have increased the frequency and intensity of natural disasters, especially in coastal areas. One of the most frequent disasters in this area is tidal flooding. Tidal flooding is a natural phenomenon that occurs due to rising sea levels overflowing onto land, often triggered by a combination of high and low tides, land subsidence, and changes in extreme weather patterns. This phenomenon is increasingly common in coastal areas, especially in Indonesia, which has the second longest coastline in the world [1]-[4].

The northern coastal areas of Java Island, such as Semarang, Pekalongan, and Jakarta, are some of the areas most vulnerable to tidal flooding. Factors such as land subsidence due to excessive groundwater extraction, coastal urbanization, and degradation of the natural environment, such as the loss of mangrove forests, further exacerbating the impacts of tidal flooding [5]-[9]. In recent decades, the frequency and extent of tidal flooding in coastal areas of Indonesia have continued to increase, causing major losses, both in terms of economy, social, and public health [10]-[14].

To overcome the impact of tidal flooding, various solutions have been proposed and implemented. One of the most common solutions is the construction of embankments or retaining walls along the coastline or river mouth. Conventional embankments made of concrete or earth materials are designed to hold back seawater from entering the land. However, this type of embankment has several limitations, especially in terms of flexibility and adaptability to dynamic changes in sea level. In addition, the materials used in conventional embankments, such as concrete and metal, are often damaged by hydrostatic pressure that continues to increase during the tidal cycle [15].

The main weakness of conventional embankments is their static nature, where their height is set for the highest predicted tide conditions. In extreme tide conditions or extraordinary events, these embankments can easily be overflowed by seawater, causing significant flooding. In addition, conventional embankments require intensive and expensive maintenance, especially in coastal areas exposed to marine corrosion and abrasion. Therefore, an innovative solution is needed that is able to adapt to fluctuating sea water levels without requiring expensive maintenance and continuous manual intervention [14].

One of the technological innovations proposed to overcome the weaknesses of conventional embankments is the floating fiber embankment. This embankment is designed to automatically adjust its height to changes in sea level. Unlike conventional static embankments, the floating fiber embankment has a top made of lightweight fiber material that can float on the water surface, while the bottom is supported by a sturdy concrete structure. When the sea level rises, this embankment is lifted automatically to prevent sea water from entering the land, and when the sea level recedes, the embankment will return to its original position [16].

The use of fiber materials in the construction of floating embankments has several advantages. Fiber is a lightweight, elastic, and corrosion-resistant material, making it very suitable for maritime environments. This material also has high resistance to deformation due to hydrostatic pressure, which allows floating fiber embankments to function for a longer period of time without significant structural damage. In addition, the elastic properties of fiber allow the embankment to adjust to changes in water levels without requiring expensive and intensive maintenance [17].

This study aims to evaluate the potential application of floating fiber embankments as an innovative solution in mitigating tidal flooding in coastal areas. The evaluation was carried out using a numerical simulation approach and laboratory experiments. Numerical simulations aim to model the mechanical behavior of floating fiber embankments under hydrostatic pressure generated by seawater, while laboratory experiments are conducted to validate the simulation results and test the performance of floating fiber embankments in real conditions. This combined approach provides comprehensive data on the effectiveness of floating fiber embankments as an adaptive solution in overcoming tidal flooding in coastal areas of Indonesia [16].

In addition, this study also explores the characteristics of fiber materials used in the construction of floating embankments, including resistance to deformation, elasticity, and resistance to corrosion. The use of fiber materials in the construction of floating embankments is expected to provide a more operationally efficient and sustainable solution in the long term, especially in coastal areas that are often affected by tidal flooding [5].

In this study, a numerical simulation approach was carried out using ANSYS software, which is based on the finite element method. This simulation aims to identify the stress, strain, and deformation that occurs in the floating fiber embankment when receiving hydrostatic pressure due to sea tides. At the same time, laboratory experiments were carried out to validate the simulation results and to ensure that the floating fiber embankment model can function properly in real conditions. Through this approach, it is hoped that the research results can provide a significant contribution to the development of more effective and efficient tidal flood mitigation technology in coastal areas [16].

In addition to technical advantages, floating fiber embankments also have better aesthetic potential than conventional embankments. Because this embankment floats and only rises at high tide, this system does not block the view of the beach, making it more environmentally friendly and suitable for application in coastal tourism areas. This makes floating fiber embankments an attractive alternative for coastal infrastructure development that not only functions as a water barrier but also maintains the aesthetic value and economic function of the tourism area [16].

Thus, this research is expected to provide a more sustainable long-term solution in facing the challenges of tidal flooding in Indonesia. In addition, the application of more flexible and adaptive floating fiber embankments is expected to reduce maintenance costs, extend service life, and increase efficiency in dealing with fluctuations in sea level due to climate change. The results of this study are also expected to be a reference for the development of policies and implementation of tidal flood mitigation technology in other coastal areas that are vulnerable to sea level rise.

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RESEARCH METHODS

Research Design

This study uses a combined method of numerical simulation and laboratory experiments to evaluate the performance of floating fiber embankments in tidal flood mitigation. This approach aims to understand how floating fiber embankments respond to hydrostatic pressure generated by sea level fluctuations, as well as to validate the performance of the embankment through physical experiments [18]-[22].

Numerical Simulation

Numerical simulations were performed using ANSYS software, which is based on the Finite Element Method (FEM). This simulation aims to evaluate the mechanical behavior of floating fiber embankments under hydrostatic pressure. The simulation stages include geometry modeling, meshing, and hydraulic analysis.

1. Geometry Modeling: The geometry of the floating fiber embankment used in the simulation has dimensions of 1 meter in length, 0.5 meters in width, and 0.5 meters in height, with a concrete base measuring 1.6 meters x 0.5 meters x 0.5 meters.
2. Meshing: After the geometry model is created, the meshing process is performed to divide the model into small elements. The mesh size chosen is 0.15 meters to increase the accuracy of the simulation.
3. Hydraulic Analysis: Simulation using ANSYS Flow Fluent module to model the hydrostatic pressure applied to the floating fiber embankment. Hydrostatic pressure is calculated based on water depth and seawater density with the formula:

$$P = \rho x g x h$$

where P is the hydrostatic pressure, ρ is the density of water, g is the acceleration due to gravity, and h is the water depth. These pressures are applied to the embankment model to determine the deformation, stress, and strain in the floating fiber embankment.

Laboratory Experiments

Laboratory experiments were conducted to validate the numerical simulation results and evaluate the performance of the floating fiber embankment under more realistic physical conditions. The floating fiber embankment prototype was made in a scale of 1:20 and tested in a 2 m x 1.2 m x 1.5 m test tank filled with water to simulate tidal conditions.

Several measuring instruments were used during the experiment, including:

1. LVDT (Linear Variable Differential Transformer): Used to measure the vertical displacement of the floating fiber embankment during testing.
2. Strain Gauge: Used to measure stress and strain at strategic points in the embankment.
3. Load Cell: Measures the hydrostatic pressure applied to the floating fiber embankment during the experiment.

The test was conducted under two main conditions, namely at full tide and at half tide. The data obtained from the measurements include deformation, stress, strain, and hydrostatic pressure. All data collected during the experiment were analyzed and compared with the simulation results to validate the accuracy of the model.

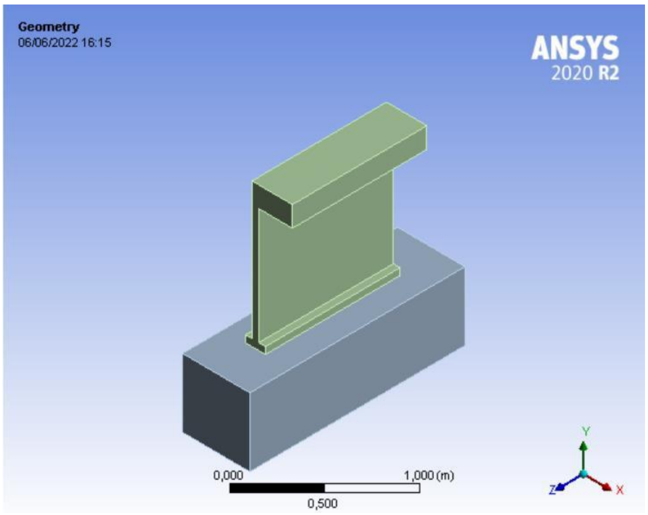

Figure 1. Geometry of Fiber Water Gate Model in ANSYS Workbench

Data Analysis

Data obtained from numerical simulations and laboratory experiments were quantitatively analyzed to evaluate the performance of floating fiber embankments. The analysis results include:

1. Deformation Analysis: The vertical displacements measured by the LVDT were compared with simulation results to assess the extent to which the embankment was deformed by hydrostatic pressure.
2. Stress and Strain Analysis: The results of strain gauge measurements are used to evaluate the stress and strain distribution on the floating fiber embankment and compared with the simulation results.
3. Result Validation: The results of the experiments and simulations were compared to validate the models used in this study. If there were significant differences, additional analysis was performed to determine the cause of the differences.

Model Validation

Model validation is done by comparing the simulation and experimental results. If the results of both show agreement, the floating fiber embankment model is considered valid. However, if there are significant differences, improvements to the model and experiments will be made to ensure accuracy.

With a combined method between numerical simulation and laboratory experiments, it is expected that the research results can provide a clear picture of the performance of floating fiber embankments in dealing with hydrostatic pressure and their application in coastal areas.

RESULTS AND DISCUSSION

Numerical Simulation Results

This study uses numerical simulation based on the Finite Element Method (FEM) with ANSYS software to evaluate the performance of floating fiber embankments in resisting hydrostatic pressure. This simulation aims to analyze the deformation, stress, and strain that occurs in floating fiber embankments when receiving pressure due to rising sea water during the tidal cycle.

The simulation results show that the floating fiber embankment experiences a maximum stress of 8231 x 10^6 Pa in the part that interacts directly with the hydrostatic pressure of seawater. This value appears mainly around the embankment that is in contact with the concrete support, where the greatest hydrostatic pressure is received [16]. In addition, the maximum strain that occurs is 0.000045 meters/meter, which is also distributed in the same area. This strain value is still within the elastic limits of the fiber material, which indicates that the embankment is able to withstand water pressure without experiencing permanent damage.

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Figure 1 shows the stress and strain distribution on the floating fiber embankment based on the simulation results. Most of the stress is concentrated at the bottom of the embankment which is directly connected to the concrete support, while the upper part that floats receives lower stress due to its buoyancy that follows the sea level.

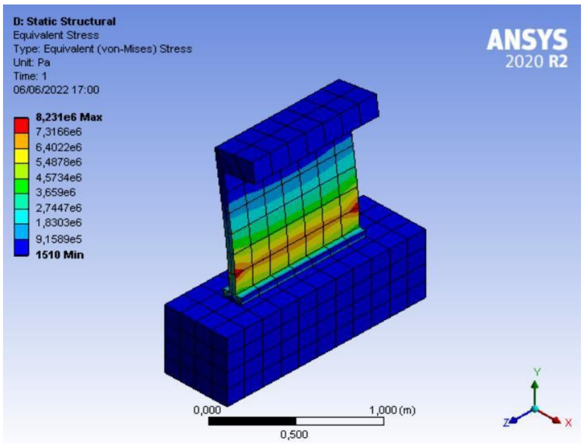

Figure 2. Stress Distribution on Floating Fiber Embankment

In addition to stress and strain, the maximum deformation that occurs in the floating fiber embankment based on the simulation is 0.43 meters. This deformation occurs at the top of the floating embankment, where hydrostatic pressure is directly applied during high tide. However, this deformation is still within safe limits and does not cause structural failure of the floating fiber embankment.

The simulation results show that the floating fiber embankment has sufficient elasticity and strength to withstand high hydrostatic pressure, while adapting to fluctuations in sea level without being damaged. Thus, the floating fiber embankment is proven to be mechanically effective in overcoming hydrostatic pressure caused by sea tides.

Laboratory Experiment Results

To validate the results of the numerical simulation, laboratory experiments were conducted using a 1:20 scale floating fiber embankment prototype. The experiments were conducted in a test tank filled with water to a certain height to simulate sea tide conditions. Measuring instruments such as LVDT (Linear Variable Differential Transformer), strain gauge, and load cell were used to measure the deformation, stress, strain, and hydrostatic pressure acting on the floating fiber embankment during the test.

The measurement results show that the maximum stress that occurs in the floating fiber embankment during the laboratory experiment is 8210 x 10^6 Pa, which is very close to the simulation results. The maximum strain value measured is 0.000044 meters/meter, which is also close to the simulation results. The maximum deformation that occurs in the floating fiber embankment during the experiment is 0.41 meters, slightly smaller than the numerical simulation results [16]. Figure 3 shows the deformation that occurs during the experiment.

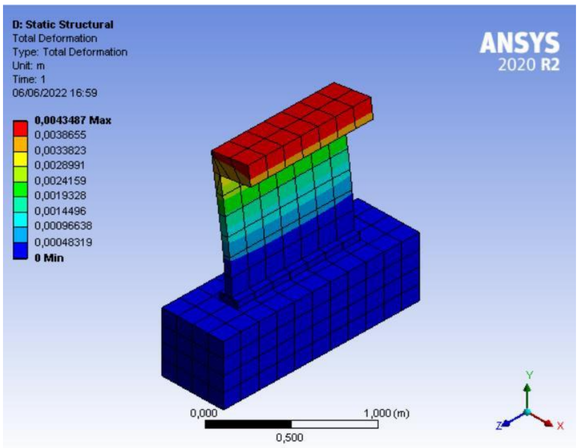

Figure 3. Deformation of Floating Fiber Embankment in Laboratory Experiment

The small differences between the simulation results and the laboratory experiments are likely due to the laboratory environment being more controlled compared to the assumptions used in the simulations. However, these differences are still within acceptable limits and do not indicate a significant discrepancy between the simulation and experimental results.

The results of this experiment show that the floating fiber embankment is able to function well in real conditions, where the deformation, stress, and strain that occur are within safe limits. In addition, the elasticity of the fiber material allows the embankment to return to its original position after the hydrostatic pressure is reduced, which shows the adaptive ability of this embankment in dealing with fluctuations in sea level.

Comparison of Simulation and Experiment Results

Table 1 below summarizes the results of the comparison between numerical simulations and laboratory experiments. The data show a fairly good agreement between the two methods, with very small differences in maximum stress, strain, and deformation.

Table 1. Comparison of Simulation and Experiment Results

Parameter	Simulation
Maximum Voltage	8231 x 10^6 Pa
Maximum Strain	0.000045meters/meter
Maximum Deformation	0.43 meters

The suitability of these results provides validation that the floating fiber embankment model tested in this study has high accuracy. These results also indicate that the floating fiber embankment is able to withstand significant hydrostatic pressure and can function well in dealing with tidal flooding in coastal areas.

Discussion

Based on simulation and experimental results, floating fiber embankments have proven to have great potential as an innovative solution in mitigating tidal flooding in coastal areas. This technology offers several advantages compared to conventional embankments. First, the ability of floating fiber embankments to automatically adjust their height to sea level fluctuations provides flexibility that conventional embankments do not have, which are generally static and cannot adapt to changes in sea level [16].

The second advantage is the elasticity and resistance of fiber material to corrosion. The fiber material used in floating embankments not only has high tensile strength, but is also able to withstand hydrostatic pressure without experiencing structural damage. In addition, resistance to corrosion makes this material suitable for use in maritime environments, where materials such as concrete or conventional metals often experience degradation due to exposure to seawater [17].

In addition, floating fiber embankments offer a more economical solution in the long term. The automated floating system eliminates the need for manual intervention and maintenance that is often required with conventional embankments. Due to their buoyancy, they are able to operate without the need for additional energy or human operators, which can significantly reduce operational costs.

However, although the results of this study show promising potential, there are several limitations that need to be considered. First, the laboratory experiments were conducted on a small scale and under controlled conditions. Therefore, further testing is needed to evaluate the performance of floating fiber embankments on a full scale in the field. In addition, more dynamic environmental conditions, such as ocean currents and high waves, also need to be taken into account in field testing to ensure the effectiveness of floating fiber embankments in dealing with extreme conditions [16].

Potential Applications in Coastal Areas

Floating fiber embankments have great potential to be applied in coastal areas of Indonesia that often experience tidal flooding. The northern coastal areas of Java, such as Semarang and Pekalongan, which often experience land subsidence, can utilize this technology as a long-term solution. In addition, other coastal areas facing the problem of rising sea levels due to climate change can also use floating fiber embankments to protect infrastructure and settlements from the impacts of tidal flooding [8], [23]-[28].

Technology also has the potential to be applied in coastal tourism areas, where aesthetics and an undisturbed environment are of primary concern. Floating fiber embankments have a minimalist design and do not obstruct the view of the beach, making them an ideal choice for coastal areas that want to maintain their tourist appeal while addressing the problem of tidal flooding.

CONCLUSION

The performance and potential of floating fiber embankments as an innovative solution in coastal flood mitigation have been evaluated through numerical simulations and laboratory experiments. The simulation results show that floating fiber embankments are able to withstand hydrostatic pressures of up to 8231 x 10^6 Pa with a maximum deformation of 0.43 meters. Laboratory experiments produce almost the same data, with a maximum stress of 8210 x 10^6 Pa and a maximum deformation of 0.41 meters, indicating consistency between simulations and tests. The adaptive ability of floating fiber embankments to sea level fluctuations has proven effective without causing structural damage. The fiber material used provides elasticity and resistance to corrosion, allowing the embankment to operate for a long time with lower maintenance costs compared to conventional embankments. Its automatic floating design also reduces the need for manual intervention, increasing operational efficiency. In addition, the potential for the application of floating fiber embankments in coastal areas that often experience tidal flooding is very large, especially in areas that are vulnerable to land subsidence and sea level rise due to climate change. With further development, including large-scale field testing and research on stronger materials, floating fiber embankments could be an effective, sustainable and economical solution to overcome tidal flooding in coastal areas of Indonesia.

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